ARMY RESEARCH LABORATORY

# Critical Adhesive Needs for Army Applications and Opportunities for Innovation

**by Robert Jensen, Wendy Kosik, Jared Gardner, and Daniel O'Brien**

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The goals of this research are to communicate the challenges of adhesive bonding for Army applications, present empirical correlations between relatively simple quasi-static coupon level testing and observed ballistic damage modes, present academic challenges that must be overcome, and finally to outline a course for minimal preliminary qualification standards that must be fulfilled for any adhesive to be considered for potential Army ground vehicle applications that encourage novel research and development into Army unique property regions.

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# CRITICAL ADHESIVE NEEDS FOR ARMY APPLICATIONS AND OPPORTUNITIES FOR INNOVATION

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## Objectives

The goals of this research are to communicate the challenges of adhesive bonding for Army applications, present empirical correlations between relatively simple quasi-static coupon level testing and observed ballistic damage modes, present academic challenges that must be overcome, and finally to outline a course for minimal preliminary qualification standards that must be fulfilled for any adhesive to be considered for potential Army ground vehicle applications that encourage novel research and development into Army unique property regions.

## Introduction

Composite integral armor (CIA) has been the subject of research for the past decade to explore the likelihood of replacing traditional rolled homogeneous armor steel in some ground vehicle applications primarily due to lower areal density and the demand for increased vehicle mobility and fuel efficiency.[1] Simplified versions of CIA consist of a ceramic strike face supported by a stiff backing plate, as illustrated in Figure 1. The incoming ballistic penetrator is ideally defeated through an erosion mechanism in the ceramic strike face while the backing plate allows for maximum dwell time by maintaining a state of compression in the ceramic. However, the complex analysis and interpretation of the response of this integrated materials system to high loading rate ballistic events remains a significant challenge.[2-5] Furthermore, as the composition of CIA includes non-metallic materials, traditional welding techniques are not an assembly option, which calls for the use of secondary polymeric adhesives to bond the armor packages together. The failure modes of CIA represent an inter-related array in which adhesive failure is particularly detrimental to both structural and ballistic performance. Regardless of the specific failure mode in any of the CIA constituent materials behind the ceramic, once the ceramic becomes unsupported the loading due to the incoming projectile is biased from a stronger compressive to much weaker tensile mode and the primary defeat mechanism of penetrator erosion is negated. While adhesive failure represents a significant element of the global failure modes in CIA, very little understanding of the adhesive response during a ballistic event is known. To compound the difficulties, very little qualitative information exists for correlating basic quasi-static coupon level testing to empirically observed ballistic testing results, leaving the basic adhesive property requirements for CIA undefined. To facilitate the optimum design of CIA systems, a better understanding of the adhesives response to high loading rates is needed. Furthermore, a standard set of relatively simple laboratory scale experiments should be identified that can facilitate the selection of adhesive systems from the wide variety of potential candidates available in the commercial sector. The development of such a standard will also drive CIA adhesive research and development by providing adhesive manufacturers and academic groups with benchmarks to strive towards and exceed. The purpose of this work is to provide context and *inspiration* for the development of a CIA adhesives performance requirements document.

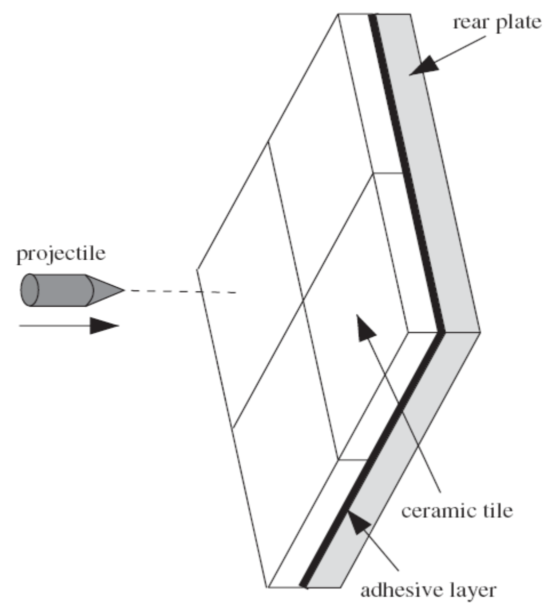


**Figure 1. Simplified schematic of ceramic based armor showing the strike face adhesively bonded to a backing plate. [6]**

## The Army's adhesive needs are largely unnoticed by industry and academia

The Army's unique adhesive requirements are currently not a significant driving factor for commercial and academic innovation. For example, a 2008 adhesive market survey concluded that there were 31 commercial polymer backbone adhesive chemistries, 105 commercial market applications, and 434 commercial adhesive manufacturers.[7] The market survey acknowledged that the adhesives industry is very dynamic with current focus pointing towards expanding production in Brazil, Russia, India, and China; environmentally friendly product development; and continuing a trend of corporate mergers and acquisitions. From an academic perspective if “Armor and Adhesive” are used as key words in a typical academic literature search only 11 citations are yielded, which do not adequately cover the depth of the issue.[8] If one undertakes an internet search with the term “Armor Adhesive” as input using a popular search engine such as Google approximately 4,450,000 hits will be generated.[9] The numerous internet search results range from hoof plate adhesives for horses, roofing adhesives, flooring adhesives, and “armor” security locks, which are all unrelated to actual CIA adhesives. Furthermore, the volume of publically released information related to armor adhesion from the Army and related defense industries is limited to relatively few papers, reports, and patents, which are clearly inadequate and can be misleading from an outside commercial formulator’s perspective with respect to necessary materials property requirements.[10-13] For comparison, a Google internet search using “MMM-A-132 aerospace film adhesive” as the key words yields approximately 2800 relevant hits,[14] and, in contrast to CIA, one can quickly and easily locate proper aerospace grade adhesives in this manner. More significantly, aerospace has accepted published testing standards that candidate adhesives must pass.[15,16] Similar standards to qualify adhesives for potential CIA applications are non-existent at this time.

## Published standards drive advancement

The publication of aerospace testing standards proceeded along a simultaneous and parallel path with the actual materials development of adhesives and was of critical importance to the eventual high acceptance levels of adhesives in this industry. In 1946 the first official standards defining the approved procedures for bonding Redux 775 were published.[17] The published standards for Redux 775 continued to evolve along with the adhesive itself until as recently as the 1990’s.[18] The initial Redux bonding standards also likely served as an effective benchmark for properties requirements needed to be attained by competing adhesive formulators. One such example was most likely the introduction of epoxy film adhesives into aircraft production in the early 1960’s.

Additionally, from the aviation based standards, it is unknown whether the adhesive is to be used for a civilian or military aircraft, or in which design or configuration. In other words, the specification is presented in such a broadly generic format to commercial adhesive formulators that the adhesive is completely decoupled from the design. Secondly, the relatively simple quasi-static coupon tests that are typically specified (lap-shear, peel, wedge, environmental exposure) further isolate the adhesive from the actual application. From an Army perspective, the aircraft industry has effectively eliminated security classification issues in broadcasting adhesive requirements to commercial formulators by completely removing any specific application use from the standard. Testing of adhesives for CIA applications currently involves fabricating the specific armor package, matching the armor package against a specific military ballistic threat at a specific velocity, and inspecting the post-test damage. While ultimately the performance of the adhesive in a CIA package against realistic ballistic threats is the final determination of success or failure, performing this type of system level testing would be much more beneficial and efficient if a quantitative ballistic figure of merit could be correlated to known coupon level quasi-static adhesion testing results. Similar standardized testing protocols applied towards CIA would effectively eliminate security classification concerns as absolutely no information regarding armor configuration or ballistic performance would be disclosed.

## Academic understanding is required

The aviation community also has an expansive history of academic involvement dating to 1943 and continuing with approximately 309 peer reviewed publications currently through 2010.[19,20] This academic partnership has lead to adhesive selection criteria for aircraft based structural designs that are well established, while the adhesive design parameters for ground vehicle applications remain poorly understood. Aircraft grade adhesives are dominated by high glass transition temperature ($T_g$) toughened epoxy thermosets, for which the strength, fatigue, and environmental durability properties are well established. Candidate adhesives for Army applications can also include high $T_g$ epoxy adhesives, but may also be expanded to include higher elongation to failure, and presumably more damage tolerant, low $T_g$ flexible epoxies, polyurethanes, polyureas, methacrylates, epoxy-acrylate interpenetrating networks, polyurethane-epoxy hybrids, silicones, and hot-melt thermoplastics. Qualitative results obtained from high loading rate impact experiments performed during ARL testing seem to indicate that high strength and low elongation to failure adhesives show poor damage tolerance. Low strength and high elongation to failure adhesives also demonstrate poor damage tolerance traits. Optimal adhesive performance, or rather a more promising potential direction under Army loading conditions, seems to occur for adhesives with both high strength and high elongation to failure.

## Army unique adhesive requirements should invite innovation opportunities

Given the fundamental scientific obstacles with Army required adhesives, there could also be significant rewards for academic and industrial partners willing to invest research and development time into the issues. From the perspective of commercial interests, assuming that the Army’s adhesive needs for CIA applications can be successfully documented through published requirements, an underlying financial motive must be present for the task to be undertaken. Aerospace benefitted economically from large "Cold War era" defense budgets in past years plus substantial growth in civilian aviation. Market surveys indicate that the automotive industry is very interested in high performance adhesives, but is also concerned about the brittle response of aircraft grade adhesives due to impact collisions.[7] One can only assume that adhesives that are found suitable for CIA could be easily transitioned to the automotive industry, where the need for lighter and more fuel efficient vehicles is becoming an increasing consumer demand.

With respect to academia, Army derived specifications for adhesives will also be unique when compared to aircraft. Army mission requirements dictate that vehicle armor performance must match against multiple threats, implying multiple armor configurations, and multiple adhesives will be needed to provide balance between structural and ballistic performance. Armor needs will encompass a very broad range of adhesive properties, many of which are likely unobtainable given current state-of-the art in materials design and processing capability. Innovation and advancement in technology requires a practical application for inspiration and motivation to pull higher risk ideas from the academic bench level into fruition in the real world. There are many historical and significant examples in which the Department of Defense provided a pivotal role in nurturing emerging technology.

From an industrial manufacturing standpoint, it is very difficult to introduce novel ideas and concepts into mature technologies, especially where the cost risk is very high, as in aviation. For applications where performance expectations are high, the final unit purchase cost of a fighter aircraft, commercial airliner, and main battle tank are approximately \$339M[21], \$150M - \$200M[22], and \$10M[23], respectively. Based solely on financial risk, an Army vehicle represents a potentially attractive platform to introduce innovative materials technology. Furthermore, the Army may also have a technology development advantage by having an engineering culture and fabrication ability that encourages a "build and shoot" approach at the subcomponent armor level, where there is no risk to human life. With a shift in perspective to more fully integrate materials specifications, academic understanding, and basic materials properties with the realization of the low cost, rapid fabrication, and testing advantages offered by the Army, the armored ground vehicle could potentially elevate to this century's premier application for development and transition of innovative materials solutions. Adhesives represent a class of materials where Army driven applications could lead to the next generation of breakthrough materials concepts from the academic laboratory bench into mainstream consumer products.

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## References

1. B.K Fink, *J. of Thermoplastic Comp. Mat.*, 2000, 13, pp 417-431.
2. L.J. Deka, S.D. Bartus, and U.K. Vaidya, *Comp. Sci. and Tech.*, 2009, 69, pp 725-735.
3. A. Tasdemirci and I.W. Hall, *Int. J. of Imp. Eng*., 2007, 34, pp 189-204.
4. S.D. Bartus and U.K. Vaidya, *J. of Adv. Mat.*, 2007, 39, pp. 3-21.
5. A.D. Resnyansky, DSTO-TR-1842 Part 1, April 2006.
6. J. Lopez-Puente, A. Arias, R. Zaera, and C. Navarro, *Int. J. of Imp. Eng*., 2005, 32, pp 321-336.
7. "Adhesives and Sealants", Global Industry Analysts, March 1, 2008.
8. ISI Web of Knowledge search "armor and adhesive", http://apps.isiknowledge.com, May 13, 2010.
9. "Armor Adhesive", www.google.com, May 13, 2010.
10. "Ceramic Array Armor", Ceradyne Inc., 6532857, May 2000.
11. J.P. Wolbert and D.M. Spagnuolo, ARL-TR-4021, February 2007.
12. Company report from Lasco International Group® outlining bonding of Spectra®, www.lascointl.com
13. R.G. O'Donnell, *J. Mat. Sci. Letters*, 1991, 10, pp 685-688.
14. "MMM-A-132 aerospace film adhesive", www.google.com, May 13, 2010.
15. MMM-A-132B NOTICE 2, "Adhesives, Heat Resistant, Airframe Structural, Metal to Metal", 14 February 2005.
16. SAE AMS-A-25463 "Adhesive, Film Form, Metallic Structural Sandwich Construction", August 1999.
17. M.A.P A D.T.D Specification, No. 775, Royal Aircraft Establishment, Farnborough, to establish approval for Redux bonding, pending Sep 1946.
18. British Aerospace (Commericial Aircraft) Ltd, Process Specification: Bonding with Redux E and Formvar powder, Ref BAEP 4020, Jan 1992.
19. A.G.H. Dietz and H. Grinsfelder, *Trans. ASME*, 1943, pp 187-191.
20 ISI Web of Knowledge search "aircraft and adhesive", http://apps.isiknowledge.com, May 13, 2010.
21. Lockheed Martin/Boeing F-22 Raptor, www.wikipedia.org
22. Boeing 787, www.wikipedia.org
23. M1 Abrams, from Secretary of Defense, "Annual Report to the President and the Congress", 1999.

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